DESIGN AND ANALYSIS OF A COMPOSITE DRIVE SHAFT FOR AN AUTOMOBILE

MUHAMMAD ZULFADHLI BIN MD ZAKI

BACHELOR OF MECHANICAL ENGINEERING WITH AUTOMOTIVE ENGINEERING,
UNIVERSITI MALAYSIA PAHANG

DESIGN AND ANALYSIS OF A COMPOSITE DRIVE SHAFT FOR AN AUTOMOBILE

MUHAMMAD ZULFADHLI BIN MD ZAKI

Report submitted in fulfilment of the requirements
for the award of the degree of
Bachelor of Mechanical Engineering

Faculty of Mechanical Engineering
UNIVERSITI MALAYSIA PAHANG

JUNE 2012

ABSTRACT

A hybrid aluminum/composite is an advanced composite material that consists of aluminum tube wound onto outside by layers of composite material. This project investigates the maximum torsion capacity of the hybrid aluminum/composite shaft for different winding angle, number of layers and stacking sequences. The hybrid shaft consists of aluminum tube wound outside of E-glass and carbon fibers/epoxy composite. The finite element method has been used to analyze the hybrid shaft under static torsion. MSC Patran/Nastran finite element software was used to perform the analysis for the hybrid shaft. The shaft model was analyzed. Isotropic properties were used for aluminum tube and orthotropic for composite materials. The results show that the static torque capacity is significantly affected by changing the winding angle, stacking sequences and the number of layers. The maximum static torsion capacity will occur in an aluminum tube wound outside by more layers of carbon fiber/epoxy composite with winding angle of 45^0.

ABSTRAK

Kacukan aluminium / komposit merupakan bahan termaju komposit yang terdiri daripada tiub aluminium digulung di luar oleh lapisan bahan komposit. Projek ini menyiasat keupayaan kilasan maksimum aci kacukan aluminium / komposit bagi sudut penggulungan yang berbeza, bilangan lapisan dan penyusunan urutan. Aci kacukan terdiri daripada tiub aluminium digulung di luar oleh E-kaca dan gentian karbon / epoksi komposit. Kaedah unsur terhingga telah digunakan untuk menganalisis aci kacukan di bawah kilasan statik. Perisian MSC Patran / Nastran telah digunakan untuk melaksanakan analisis bagi aci kacukan. Model aci telah dianalisis. Sifat isotropi telah digunakan bagi tiub aluminium dan orthotropic bagi bahan komposit. Hasil kajian menunjukkan bahawa keupayaan kilasan statik dipengaruhi oleh perubahan sudut penggulungan, penyusunan urutan dan bilangan lapisan. Keupayaan kilasan statik maksimum akan berlaku di dalam tiub aluminium yang digulung oleh lapisan komposit gentian karbon / epoksi dengan sudut penggulungan 45^{o}.

TABLE OF CONTENTS

CHAPTER 1

INTRODUCTION

1.1 PROJECT BACKGROUND

A drive shaft is a mechanical device for transferring power from the engine or motor to the point where useful work is applied. Most engines or motors deliver power as torque through rotary motion. This is extracted from the linear motion of pistons in a reciprocating engine. From the point of delivery, the components of power transmission from the drive train. The drive shafts are carriers of torque which are subject to torsion and shear stress, which represents the difference between the input force and the load. They thus need to be strong enough to bear the stress, without imposing too great an additional inertia by virtue of the weight of the shaft.

Traditionally, drive shaft is from steel which transfer power from the transmission to the rear axle of the vehicle. As a direct response to industry demand, for greater performance and efficiency in light trucks, vans and high performance automobiles, the graphite, carbon, fiberglass, and aluminum driveshaft tube were developed. The main reason for this is a significant saving in weight of drive shaft. The composite drive shaft has a mass of about 2.7 kg, while the amount for steel drive shaft is about 10 kg [1]. The use of composite drive shafts in race cars has gained great attention in recent decades. When a steel drive shaft break its components, are thrown in all directions such as balls, it is also possible that the drive shaft makes a hole in the ground and throw the car into the air. But when a composite drive shaft breaks, it is divided into fine fibers that do not have any danger for the driver.

Steel is an alloy that consists mostly of iron and has carbon content between 0.2% and 2.1% by weight, depending on the grade. Carbon is the most common alloying material for iron, but various other alloying elements are used, such as manganese, chromium, vanadium, and tungsten [2]. The Original Equipment Manufacturer or OEM steel drive shafts are rated for less heavy-duty service than other types of steel drive shafts. Usually steel drive shafts can handle about 350 pounds per foot, or about 350 to 400 horsepower. This is the lowest performance level for steel drive shafts. From this, it can’t use for the high weight automobile.

Composite drive shafts are made of carbon and polymer fiber that is designed to break into small fiber fragments or “broom” upon failure, posing little danger. Composite drive shafts are also lightweight, requiring less energy to spin, effectively increasing the amount of power that the engine can transmit to the wheels. Composite materials, often shortened to composites or called composition materials, are engineered or naturally occurring materials made from two or more constituent materials with significantly different physical or chemical properties which remain separate and distinct at the macroscopic or microscopic scale within the finished structure. According to an Advanced Composites Products and Technology Inc, a test, a composite driveshaft in a supercharged LT1 Camaro on a DynoJet chassis dynamometer showed a power gain at the wheels that increased as the engine made more power. At 3000 rpm, the shaft puts nine additional horsepower to the ground, and at 5000 rpm when the engine was making almost twice the power, this number nearly doubled [3].

The advanced composite materials such as graphite, carbon, Kevlar and glass with suitable resins seem ideally suited for long, power drive shaft. The drive shaft used in automotive is exploiting composite material technology in order to obtain the reduction of the weight without a decrease in vehicle quality and reliability.

1.2 PROBLEM STATEMENT

The drive shaft, which is usually made from seamless steel tubing, transfers engine torque from the transmission to the rear driving axle. At the present time, a limited number of vehicles are equipped with fiber composite reinforced fiberglass, graphite, and aluminum drive shafts. The advantages of using these materials are weight reduction, torsional strength, fatigue resistance, easier and better balancing, and reduced interference from shock loading and torsional problems. Some drive shafts are fitted with a torsional damper to reduce torsional vibrations.

The variety of material has its own characteristics, types of properties and different structural component. Steel is an alloy that consists mostly of iron and has a carbon content which act as a hardening agent, preventing dislocations in the iron atom crystal lattice from sliding past one another. Varying the amount of alloying elements and the form of their presence in the steel precipitated phase controls qualities such as the hardness, ductility, and tensile strength of the resulting steel. Steel with increased carbon content can be made harder and stronger than iron, but such steel is also less ductile than iron. Today, steel is one of the most common materials in the world, but its disadvantages are the weight. Steel also classified as an isotropic material which the properties of a material are the same in all directions.

Advanced composites utilize a combination of resins and fibers, customarily carbon/graphite, Kevlar, or fiberglass with an epoxy resin. The fibers provide higher stiffness, while the surrounding polymer resin matrix holds the structure together. The fundamental design concept of composites is that the bulk phase accepts the load over a large surface area, and transfers it to the reinforcement material, which can carry a greater load. These materials have a higher stiffness to weight or strength to weight ratio than metals. This means metal parts can be replaced with lighter weight parts manufactured from advanced composites. Generally, carbon-epoxy composites are two thirds the weight of aluminum, and two and a half times as stiff. Composites are resistant to fatigue damage and harsh environments, and are repairable. Composite also classified as non-isotropic material (independent of direction of applied force) or rather typically as an anisotropic material (different depending on the direction of the applied force or load).

Today, composite drive shafts are mostly used in vehicles. It is generally subjected to torsional stress and bending stress due to weight of components. Thus, these rotating components are susceptible to fatigue by the nature of their operation. From this, the composite drive shaft which designed by winding angle, stacking sequence and number of layers of laminated material must be analyzed to know how strong it can handle the load. Thus, this project analyzes the best combination method of laminate material of composite drive shaft.

1.3 PROJECT OBJECTIVES

The objectives of the project are:

a) To design and analyzed drive shaft with composite material which are glass fiber and carbon fiber.
b) To design and analyzed a composite drive shaft with specific winding angle for an automobile.
c) To design and analyzed a composite drive shaft with different stacking sequence for an automobile.
d) To design and analyzed a composite drive shaft with different number of layers for an automobile.
e) To analyze the static torque capacity of the composite drive shaft for an automobile.

1.4 PROJECT SCOPE OF ACTIVITY

This project is focusing on design a composite drive shaft which was subjected to static torque capacity and inspection by using finite element analysis software. The scope of this study includes:

a) The drive shaft was designed using the Solidwork design software.
b) The drive shaft design was imported from Solidwork to MSC Patran finite element analysis software.
c) The drive shaft was mashed and the model will be set with a number of material layers, winding angle and stacking sequence of the material.
d) The material of the drive shaft was chosen from the composite material such as E-Glass/Epoxy or high Strength carbon/Epoxy.
e) The analysis of a composite drive shaft was analyzed to produce the stress strain, and deflections result.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

The advanced composite materials such as graphite, carbon, Kevlar and glass with suitable resins are widely used because of their high specific strength (strength / density) and high specific modulus (modulus / density) [4]. Weeton et al [5] described the application possibilities of composites in the field of the automotive industry such as elliptic springs, drive shafts, leaf springs and etc. Beardmore et.al [6, 7] highlighted the potential for composites in structural automotive applications from a structural point of view. The weight reduction of the drive shaft can have a certain role in the general weight reduction of the vehicle and is a highly desirable goal, if it can be achieved without an increase in cost and a decrease in quality and reliability. It is possible to reduce the weight of the drive shaft considerably by optimizing the design parameters by satisfying the all constraints.

Advantages of composite drive shafts include: significant weight reduction, reduced bearing and journal where, symmetric composite assure dynamic balance and increased operating speeds, electrically conductive or non-conductive, custom end-fitting configurations, corrosion resistant, reduced noise, vibration and harshness (NVH), long fatigue life. Since carbon fiber epoxy composite materials have more than four times specific stiffness of steel or aluminum materials, it is possible to manufacture composite drive shafts in one-piece without whirling vibration over 9200 rpm [8].

Apart from higher specific stiffness and strength, the polymer matrix composites also offer superior vibration damping and fatigue characteristics as well as excellent corrosion resistance over metals. However, because of the higher material cost of carbon fiber/epoxy composite materials, rather cheap aluminum materials may be used partly with composite materials such as in a hybrid type of aluminum/composite drive shaft, in which the aluminum has a role to transmit the required torque, while the carbon fiber/epoxy composite increases the bending natural frequency [9].

Moreover, an optimization study was carried out to optimize the composite drive shaft in terms of composite materials, winding angle, stacking sequence and number of layers and the end joints of the drive shaft [10-14]. Furthermore, a compressive pre-load method was developed to reduce the thermal residual stress and improve the fatigue characteristics of a hybrid aluminum/composite shaft [15].

2.2 COMPOSITE MATERIALS

2.2.1 Introduction to Composite Materials

Most composites have strong, stiff fiber in a matrix which is weaker and less stiff. The objective is usually to make a component which is strong and stiff, often with a low density. Commercial material commonly has glass or carbon fibred in matrices based on thermosetting polymers, such as epoxy or polyester resins. Sometimes, thermoplastic polymers may be preferred, since they are moldable after initial production. There are further classes of composite in which the matrix is a metal or a ceramic. For the most part, these are still in a developmental stage, with problems of high manufacturing costs yet to be overcome. Furthermore, in these composites the reasons for adding the fibers (or, in some cases, particles) are often rather complex; for example, improvements may be sought in creep, wear, fracture toughness, thermal stability, and etc. This software package covers simple mechanics concepts of stiffness and strength, which, while applicable to all composites, are often more relevant to fibred-reinforced polymers.

2.2.2 Physical Properties of Composite Material

Composites are made up of individual materials referred to as constituent materials. There are two categories of constituent materials: matrix and reinforcement. At least one portion of each type is required. The matrix material surrounds and supports the reinforcement materials by maintaining their relative positions. The reinforcements impart their special mechanical and physical properties to enhance the matrix properties. A synergism produces material properties unavailable from the individual constituent materials, while the wide variety of matrix and strengthening materials allows the designer of the product or structure to choose an optimum combination.

Engineered composite materials must be formed to shape. The matrix material can be introduced to the reinforcement before or after the reinforcement material is placed into the mould cavity or onto the mould surface. The matrix material experiences a melding event, after which the part shape is essentially set. Depending upon the nature of the matrix material, this melding event can occur in various ways such as chemical polymerization or solidification from the melted state.

Most commercially produced composites use a polymer matrix material often called a resin solution. There are many different polymers available depending upon the starting raw ingredients. There are several broad categories, each with numerous variations. The most common are known as polyester, vinyl ester, epoxy, phenolic, Polyimide, polyamide, polypropylene, PEEK, and others. The reinforcement materials are often fibers but also commonly ground minerals. The various methods described below have been developed to reduce the resin content of the final product, or the fiber content is increased. As a rule of thumb, lay up results in a product containing 60% resin and 40% fiber, whereas vacuum infusion gives a final product with 40% resin and 60% fiber content [16]. The strength of the product is greatly dependent on this ratio.

2.2.3 Mechanical Properties of Composite Material

The physical properties of composite materials are generally not isotropic (independent of direction of applied force) in nature, but rather are typically anisotropic (different depending on the direction of the applied force or load). For instance, the stiffness of a composite panel will often depend upon the orientation of the applied forces and/or moments. Panel stiffness is also dependent on the design of the panel. For instance, the fiber reinforcement and matrix used the method of panel builds, thermoset versus thermoplastic, type of weave, and orientation of fiber axis to the primary force.

In contrast, isotropic materials (for example, aluminum or steel), in standard wrought forms, typically have the same stiffness regardless of the directional orientation of the applied forces and/or moments.

The relationship between forces/moments and strains/curvatures for an isotropic material can be described with the following material properties: Young's Modulus, the shear Modulus and the Poisson's ratio, in relatively simple mathematical relationships.

a) Classification of Composite Materials

Since the reinforcement material is of primary importance in the strengthening mechanism of a composite, it is convenient to classify composites according to the characteristics of the reinforcement. The following three categories are commonly used.

Table 2.1: Types and General Characteristics of Composite Material

Material	Characteristics
Fiber	
Glass	High strength, low stiffness, high density and low cost; E (calcium aluminoborosilicate) and S (magnesia-aluminosilicate) types commonly used.
Graphite	Available as high modulus or high strength, low cost, less dense than glass.
Matrix materials	
Thermosets	Epoxy and polyester, with the former most commonly used; ordinary are phenolics, fluorocarbons, and silicon.
Thermoplastics	Polyetheretherketone; tougher then thermosets, but lower resistance to temperature.
Metals	Aluminum, aluminum-lithium, magnesium, and titanium; fiber is graphite, aluminum oxide, silicon carbide and boron.

Source: Mallick, P.K. 1997 [17]

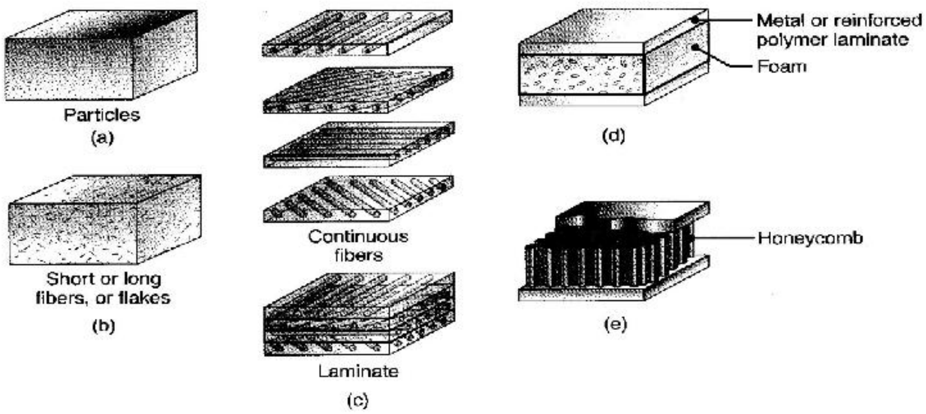

Figure 2.1: Schematic illustration of methods of reinforcing plastics (metrix) (a) perticles, (b) short or long fiber or flakes, and (c) through (e) continuous fibers. The laminate structures shown in (d) can be produced from layers of continuous fibers or sandwich structures using a foam or honeycomb core.

Source: Mallick, P.K. 1997 [17]

2.2.4 Categories of fiber-reinforced composite materials

Fiber-reinforced composite materials can be divided into two main categories normally referred to as short fiber-reinforced materials and continuous fiber-reinforced materials. Continuous reinforced materials will often constitute a layered or laminated structure. The woven and continuous fiber styles are typically available in a variety of forms, being pre-impregnated with the given matrix (resin), dry, uni-directional tapes of various widths, plain weave, harness satins, braided, and stitched.

The short and long fibers are typically employed in compression moulding and sheet moulding operations. These come in the form of flakes, chips, and random mate (which can also be made from a continuous fiber laid in random fashion until the desired thickness of the ply or laminate is achieved).

Fiberglass is likely the best know fiber reinforced composite but carbon-epoxy and other advanced composites all fall into this category. The fibers can be in the form of long continuous fibers, or they can be discontinuous fibers, particles, whiskers and even weaved sheets. Fibers are usually combined with ductile matrix materials, such as metals and polymers, to make them stiffer, while fibers are added to brittle matrix materials like ceramics to increase toughness. The length-to diameter ratio of the fiber, the strength of the bond between the fiber and the matrix, and the amount of fiber are variables that affect the mechanical properties. It is important to have a high length to diameter aspect ratio so that the applied load is effectively transferred from the matrix to the fiber. The types of fiber-reinforced composite materials were shown in figure 2.2.

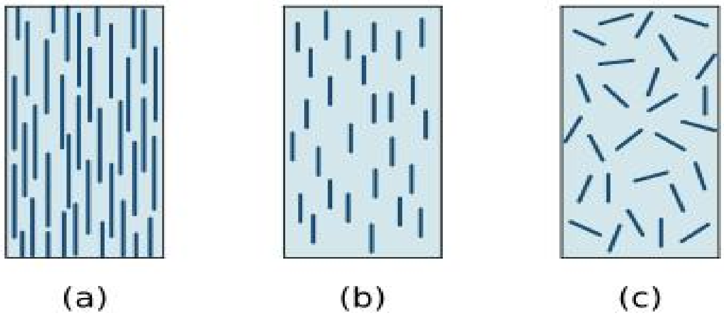

Figure 2.2: Typologies of fiber-reinforced composite materials: (a) continuous fiber-reinforced; (b) discontinuous aligned fiber-reinforced; (c) discontinuous random-oriented fiber-reinforced.

Source: Nielsen, L.E., and Landel, R.F. 1994 [18]

a) Glass fiber

Glass fiber (also spelled glass fiber) is a material consisting of numerous extremely fine fibers of glass. Glass fiber is commonly used as an insulating material and as a reinforcing agent for many polymer products, to form a very strong and light fiber-reinforced polymer (FRP) composite material called glass-reinforced plastic (GRP), popularly known as "fiberglass". Glass fiber has roughly comparable properties to other fibers such as polymers and carbon fiber. Although not as strong or as rigid as carbon fiber, it is much cheaper and significantly less brittle. Glass fiber is the most common fiber and is usually used for the reinforcement of polymer matrices which has a high tensile strength and fairly low density (2.5 g/cc).

Glass fiber is formed when thin strands of silica-based or other formulation glass are extruded into many fibers with small diameters suitable for textile processing. The technique of heating and drawing glass into fine fibers has been known for millennia, however, the use of these fibers for textile applications is more recent. Until this time, all glass fiber had been manufactured as staple (a term used to describe clusters of short lengths of fiber) [19].

The types of glass fiber most commonly used are mainly E-glass (alumino-borosilicate glass with less than 1% w/w alkali oxides, mainly used for glass-reinforced plastics), but also A-glass (alkali-lime glass with little or no boron oxide), E-CR-glass (alumino-lime silicate with less than 1% w/w alkali oxides, has high acid resistance), C-glass (alkali-lime glass with high boron oxide content, used for example for glass staple fibers), D-glass (borosilicate glass with high dielectric constant), R-glass (alumino silicate glass without MgO and CaO with high mechanical requirements), and S-glass (alumino silicate glass without CaO but with high MgO content with high tensile strength) [20]. The glass fiber and its molecular structure were shown in figure 2.3 below.

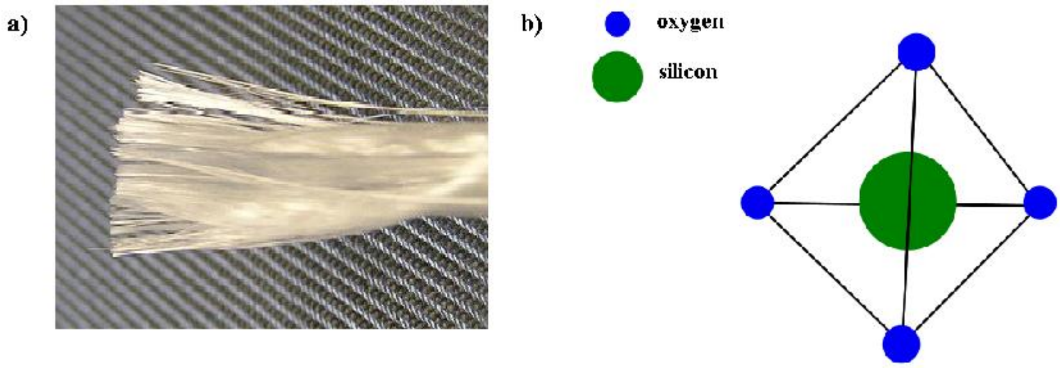

Figure 2.3: a) Bundle of glass fibers; b) Molecular Structure of Glass

Source: Mallick, P.K. 1997 [17]

Glass fibers are useful thermal insulators because of their high ratio of surface area to weight. However, the increased surface area makes them much more susceptible to chemical attack. By trapping air within them, blocks of glass fiber make good thermal insulation, with a thermal conductivity of the order of 0.05 W/(m·K) [21]. Besides that, glass fiber also has tensile properties which are shown in table 2.2.

Table 2.2: Tensile properties of Glass Fiber

Fiber type	**Tensile strength (MPa)**	**Compressive strength (MPa)**	**Density (g/cm^3)**	**Thermal expansion µm/(m °C)**	**Softening temperature (°C)**
E-glass	3445	1080	2.58	5.4	846
S-2 glass	4890	1600	2.46	2.9	1056

Source: Frederick T. Wallenberger; Paul A. Bingham (October 2009) [22]

The strength of glass is usually tested and reported for "virgin" or pristine fibers, those that have just been manufactured. The freshest, thinnest fibers are the strongest because the thinner fibers are more ductile. The more the surface is scratched, the less the resulting tenacity [23]. Because glass has an amorphous structure, its properties are the same along the fiber and across the fiber [24]. Humidity is an important factor in the tensile strength. Moisture is easily adsorbed, and can worsen microscopic cracks and surface defects, and lessen tenacity.

In contrast to carbon fiber, glass can undergo more elongation before it breaks. There is a correlation between bending diameter of the filament and the filament diameter [25]. The viscosity of the molten glass is very important for manufacturing success. During drawing (pulling of the glass to reduce fiber circumference), the viscosity must be relatively low. If it is too high, the fiber will break during drawing. However, if it is too low, the glass will form droplets rather than drawing out into fiber.

b) Carbon fiber

Carbon-fiber-reinforced polymer or carbon-fiber-reinforced plastic (CFRP or CRP or often simply carbon fiber), is a very strong and light fiber-reinforced polymer which contains carbon fibers. The polymer is most often epoxy, but other polymers, such as polyester, vinyl or nylon, are sometimes used.

Although it can be relatively expensive, it has many applications in aerospace and automotive fields, as well as in sailboats, and notably finds use in modern bicycles and motorcycles, where its high strength to weight ratio and good rigidity is of importance. Improved manufacturing techniques are reducing the costs and time to manufacture, making it increasingly common in small consumer goods as well, such as laptops, tripods, and fishing rods.

Other terms used to refer to the material are carbon fiber, graphite-reinforced polymer or graphite fiber-reinforced polymer. It's called as graphite fiber (graphite fiber) because graphite is a form of pure carbon. In graphite the carbon atoms are arranged into big sheets of hexagonal aromatic rings.

Carbon-graphite also classified as an advanced composite. Carbon fibers are the material of choice. Carbon is a very light element, with a density of about 2.3 g/cc and its stiffness is considerable higher than glass. Carbon fibers can have up to 3 times the stiffness of steel and up to 15 times the strength of construction steel. The graphitic structure is preferred over the diamond-like crystalline forms for making carbon fiber because the graphitic structure is made of densely packed hexagonal layers, stacked in a lamellar style. This structure results in mechanical and thermal properties are highly anisotropic and this gives component designers the ability to control the strength and stiffness of components by varying the orientation of the fiber.

c) Polymer

The strong covalent bonds of polymers can lead to impressive properties when aligned along the fiber axis of high molecular weight chains. Kevlar is an aramid (aromatic polyamide) composed of oriented aromatic chains, which makes them rigid rod-like polymers. Its stiffness can be as high as 125 GPa and although very strong in tension, it has very poor compression properties. Kevlar fibers are mostly used to increase toughness in otherwise brittle matrices.

d) Ceramic

Fibers made from materials such as Alumina and SiC (Silicon carbide) are advantageous in very high temperature applications, and also where environmental attack is an issue. Ceramics have poor properties in tension and shear, so most applications as reinforcement are in the particulate form. The properties of reinforcing fibers are shown in table 2.3 below.

Table 2.3: Typical Properties of Reinforcing Fibers

Type	Tensile Strength (MPa)	Elastic modulus (GPa)	Density (kg/m^3)	Relative cost
Carbon				
High strength	3000	275	1900	Low
High modulus	2000	415	1900	Low
Glass				
E-type	3500	73	2480	Lowest
S-type	4600	85	2540	Lowest
Kevlar				
29	2800	62	1440	High
49	2800	117	1440	High
129	3200	85	1440	High

Source: Schwartz, M. 1997 [26]

2.3 Aluminum and Aluminum Alloys

Aluminum was first produced in 1825. The important factors in selecting aluminum (Al) and its alloys are their higher strength-to-ratio, resistance to corrosion by many chemicals, high thermal and electrical conductivity, appearance and ease of formability.

The principal uses of aluminum and its alloys are in containers and packaging (aluminum cans and foil), buildings and other types of construction, transportation (aircraft and automobiles) and portable tools. Table 2.4 shows the selected aluminum alloys at room temperature based on their properties.

Table 2.4: Properties of Aluminum Alloy at room temperature

Alloy (UNS)	Temper	Ultimate tensile Strength (MPa)	Yield strength (MPa)	Elongation in 50mm (%)
1100 (A91100)	O	90	35	35-45
1100	H14	125	120	9-20
2024 (A92024)	O	190	75	20-22
2024	T4	470	325	19-20
3003 (A93003)	O	110	40	30-40
3003	H14	150	145	8-16
5052 (A95052)	O	190	90	25-30
5052	H34	260	215	10-14
6061 (A96061)	O	125	55	25-30
6061	T6	310	275	12-17
7075 (A97075)	O	230	105	16-17
7075	T6	570	500	11

*O = Annealed (from cold worked); H = Strain hardened by cold working;
T = Heat treated

Source: ASM *Specialty Handbook: Aluminum and Aluminum Alloys*, ASM International, 1993 [27]